FGD liner experiments with wetlands: Second-year results

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Introduction

This paper presents the second year results of an experiment designed to determine if flue gas desulfurization (FGD) material can be used as a liner material for wetlands designed to improve water quality. The construction of artificial wetlands for wastewater treatment often needs impermeable clays for liners. Liners or relatively impervious site soils are very important to the success of constructed treatment wetlands in areas where ground water levels are typically close to the ground surface (Kadlec and Knight, 1996). The liner is necessary not only to protect groundwater resources but also to ensure that there is adequate water in the wetland to support appropriate aquatic life, particularly wetland vegetation.

Our study, carried out at the Olentangy River Wetland Research Park, investigated the use of FGD material from sulfur scrubbers as possible liner material for constructed wetlands. While several studies (cited in Ahn et al., 1998) have investigated the use of FGD material to line ponds, no studies have investigated the use of this material as a liner for constructed wetlands. In our study, we used experimental mesocosms to see the effect of FGD liner materials in constructed wetlands on water quality and on wetland plant growth. This paper presents the results of nutrient analyses and physicochemical investigation of leachate and surface outflow water samples collected from the mesocosms. Plant growth and biomass of wetland vegetation are also included in this paper. First-year results were reported by Ahn et al. (1998). The overall goal of this study is the identification of advantages and disadvantages of using FGD by-product as an artificial liner in constructed wetlands. This goal is accomplished by:

1. investigating the effects of a FGD by-product on water quality in wetland systems;
2. investigating the effects of a FGD by-product on ecosystem health, e.g., plant growth; and
3. describing the biogeochemical dynamics of a wetland system with FGD.

Methods

Mesocosm installation in 1997

In March 1997, a set of 20 flow-through mesocosms (1 m^2 x 0.6 m polyethylene tubs) were positioned at the ORWRP, a 12-ha research site located on the Columbus campus of The Ohio State University, to investigate the effect of FGD liner on ecological functions of wetlands. FGD by-products were randomly assigned to half of the mesocosms; the other half with no FGD liner in the tubs served as controls (Fig. 1). Mesocosms were buried in the ground to insulate roots against freezing. Each mesocosm received 10 cm of noncalcareous river pea gravel (completely covering the drain to the standpipe) overlain by 10 -15 cm FGD by-product generated from an Ohio electric power plant. Fifteen to twenty cm of topsoil obtained during the excavation of the mesocosm site was placed on top (Figure 1). The FGD by-product (Table 1) placed in the mesocosms was compacted in each mesocosm, but soil was not compacted and substantial settling occurred. Microtopographic variations (1 -3 cm) within the mesocosms after wetting were unavoidable even though we did spread out the material and smoothed the bottom by hand. The FGD by-product used in the experiment was a combination of fly-ash to filter-cake ratio of 1.25: 1 and 5 % lime.

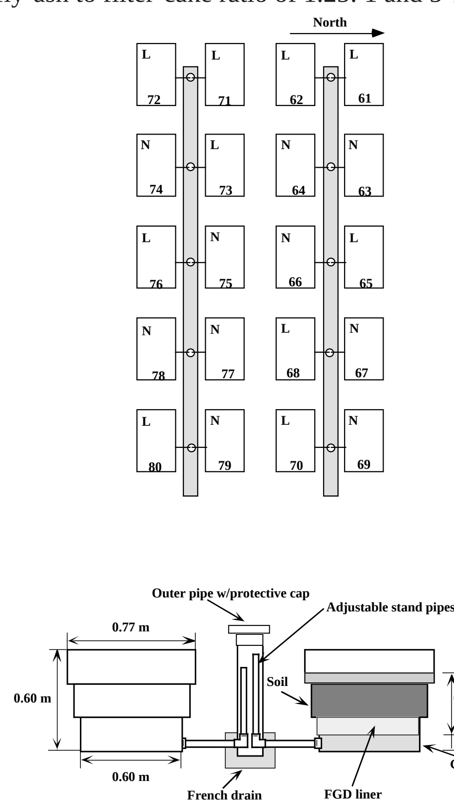

Figure 1. Diagrams of 20 mesocosms and drain system. Mesocosms are identified by numbers and by presence or absence of FGD liner material (L = liner, N = no liner).

Table 1. Chemical analysis of FGD used for the experiment

pH	10.6
Total chemical analysis	
Major and trace elements,	ppm
Al	25,511
As	107
B	356
Ba	140
Be	6
Ca	146,086
Co	20
Cr	51
Cu	49
Fe	85,018
K	2,693
Li	38
Mg	3,680
Mn	130
Mo	15
Na	722
Ni	48
P	573
Pb	15
S	84,984
Sb	22
Si	342
Sr	254
V	74
Zn	133

Mesocosm hydrology

A water delivery system (Fig. 2) was constructed to simulate natural flows of contaminated surface runoff into natural or constructed wetlands. This was accomplished through a series of manifolds and valves that distributed similar volumes of water pumped from the Olentangy River to each of the twenty mesocosms. This water, which is contaminated by agricultural and urban runoff, was first stored in two 1600-L tanks. These tanks were connected in such a way that they could be isolated or run in series. This would allow the chemistry of the water delivered to half of the mesocosms to be varied, while using the other half as a control. A mercury float switch constantly maintained water levels and the resulting flow to the mesocosms. A #20 mesh pre-filter was installed and cleaned daily during data collection to prevent clogging in the numerous pipes and valves involved in the water distribution system.

A pulse system was used that delivered a similar, per-day volume, but instead flowed rapidly for one hour per day. A common sprinkler system timer was used to program the pulse time and duration. Water levels and water flow were measured to maintain uniform hydrology in the 20 mesocosms with no differences between liner and no-liner treatments. Water level was checked three times a week during the experiment. The flow rate of river water into the

Figure 2. The FGD mesocosm experimental layout at the Olentangy River Wetland Research Park.

mesocosms was measured with a graduated cylinder and a timer. Quite similar hydrology in liner and no-liner mesocosms was maintained. Comparison of hydrology among the treatments in the second-year experiment did not show any significant differences (p = 0.52 by flow rate, 900mL/min) (Fig. 3).

Experimental design in 1998

In 1998, the experiment begun in 1997 was continued but with plants now consisting of a much greater biomass than in the 1997 study. In the second-year study we added

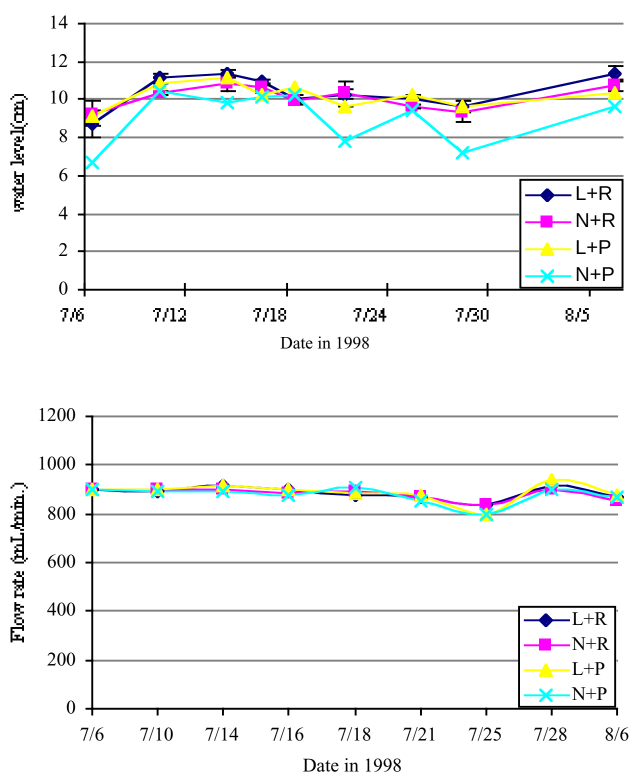

Figure 3. The mesocosm hydrology in a) water level and b) flow rate during the experiment (L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

phosphorus as super phosphate (P_2O_5, 46%) to one tank to provide high-P loading to 10 of the mesocosms, simulating the phosphorus concentration of treated wastewater going to a treatment wetland. Thus, the experimental design of the second-year study included four different treatment schemes such as liner plus riverwater (L +R), no-liner plus riverwater (N+R), liner plus P-spike water (L+P), and no-liner plus P-spiked water (N+P).

Field sampling and analysis for water quality measurement

Water sampling was done three times per week for four weeks. Surface outflow samples were collected directly from the mesocosm outlets and leachate was obtained from the standpipe connected to the bottom layer of the mesocosms. Two mesocosms that were not hydrologically sound in leachate collection due to the lack of leachate coming up in the standpipe were removed from the study. Therefore, only 18 mesocosms were included in the leachate analysis and all 20 mesocosms were included in the analysis of outflow. Water samples were collected in 500 ml polyethylene bottles. Prior to sample collection, all bottles were hand-washed with 50 % HCl followed by a thorough triple rinse with distilled water. Sample bottles were transported to the field in a cooler and all samples were kept in a freezer at 4°C until analysis. One sample was filtered through a 0.45 mm filter and placed in a freezer for later orthophosphate analysis. Filters were soaked for approximately 24 hr in distilled water to remove contamination. The other unfiltered samples were preserved by acidification with 2 mL 36 N H_2SO_4 per L of sample (to pH < 2) immediately upon return to the Ecosystem Analytical Laboratory. A YSI Multiparameter Water Quality Data Transmitter was used to collect pH, conductivity, dissolved oxygen, temperature, and oxidation-reduction potential measurements through the period of experiment. The YSI was calibrated on a weekly basis during the experiment.

Laboratory analyses

Turbidity was determined on the day of sampling with a Hach Model 18900 Ratio Turbidimeter. Samples were analyzed later by a Lachat QuickChem IV Flow Injection Analysis (FIA) System. All analyses for total phosphorus (APHA, 1992: Method 4500-PF), orthophosphate (APHA, 1992: Method 4500-PF) and NO2+NO3-N (APHA, 1992: Method 4500-NO3E) were done on the Lachat autoanalyzer. All samples and standards were at room temperature and were vigorously mixed by inversion for analysis. Five prepared standards, a check standard, and distilled water blank were run each time that an analysis was conducted. Standards were always within 10% of the prescribed values.

Plant morphometry

Planting and survey for the growth of wetland vegetation are well described in the first-year report (Ahn et al., 1998). Number of stems, number of stems bearing flowers and stem lengths were investigated weekly in each mesocosm during the second-year experiment (June 30 to August 17, 1998). For stem length, 20 randomly chosen stems were measured for each mesocosm with a ruler.

Plant Harvesting and element analysis

After two growing seasons, plant biomass harvesting was carried out at the end of second-year experiment (August 20 through September 13, 1998). All aboveground stems were cut at the soil surface. Belowground biomass was harvested. Plant samples were placed in plastic bags and weighed in the field with a hanging balance (accuracy to 40 g). Subsamples were taken to a laboratory where both wet weight and dry weight were determined to estimate dry/wet ratios. Ratios were multiplied by total wet weight of the biomass from each mesocosm to estimate each dry weight production. The subsamples were allowed to dry until constant weight at 60 °C, and some of them were ground to pass through a 1mm screen using Wiley Mill. Five grams of each sample kept in a paper coin envelope were sent for the analysis of plant tissue elements by Inductively Coupled Plasma (ICP) emission spectrometry to the Ohio Agricultural Research and Development Center (OARDC) Star lab in Wooster, Ohio. The samples included aboveground and belowground biomass of the plants.

Element analysis of surface soil

Soil samples were also taken after aboveground biomass harvesting from the approximately top 5 cm of the surface of the mesocosm soil to see if FGD material buried on the bottom of the mesocosms translocates into the upper layer of soil, which may impact on surface water quality of the wetlands. Three small samples were taken from each mesocosm and made into a composite sample to represent each mesocosm. The soil samples were air-dried and ground using a mortar and pestle to pass through a 2 mm screen to sieve out stones. The samples prepared were sent to the Star Lab at OARDC in Wooster, Ohio, for the analysis of the elements by ICP.

Data analysis

Data analyses were conducted as a two-way analysis of variance using the General Linear Model (GLM) procedure in SAS (SAS Institute, 1988) with FGD liner and phosphorus addition as main effects for all the items measured in water quality, plant morphometric measurements, plant biomass and element analysis. To analyze plant morphometry and water quality data, the averages of the parameters measured were calculated for each sampling day and then used for statistical analysis. Orthophosphate concentrations of leachate obtained below the detection limit were treated as 0. Thus, calculated concentrations represent minimum estimates. Duncan's multiple tests were used to test all pairwise contrasts of means for significance at $P < 0.05$. A LSD (least significant difference) test was additionally run for elemental analysis among the treatments to detect the difference, if any, more vigorously (Steel et al., 1997).

Result and Discussion

Mesocosm water quality 1998

Conductivity

Data showed a significant difference in leachate conductivity between lined and unlined mesocosms ($p < 0.05$) (Fig. 4). Liner treatment increased the conductivity of leachate significantly, which was also much higher than the values from previous year (Table 2). No difference between the treatments was observed in surface outflow.

pH

Generally, the pH of water samples was lower and more stabilized in the second year compared to the first-year (Table 2). It seems that the high pH caused by FGD liner treatment settled down over time, whereas the pH of leachate was still significantly higher ($p < 0.05$) in lined mesocosms than in unlined mesocosms (Fig. 5). No difference was observed between two different phosphorus loadings.

Redox

The redox values in both outflow and leachate were much lower during the second-year experiment compared to those of the first year, reflecting much reduced condition developed in soil over time (Table 2; Fig. 6). Most of the leachate redox was below 100 mV, indicating the leachate was reduced enough for ferric iron (Fe^{3+}) to convert to ferrous iron (Fe^{2+}). Iron reduction would influence phosphorus dynamics in the system because the inorganic phosphorus adsorbed with iron and aluminum oxyhydroxide can be released back to the water from the sediment (Reddy and D'Angelo, 1994). Also, nitrogen and manganese are known to be reduced at less than 100mV of redox potential. The lowered redox is thought to have stimulated nitrate removal of the leachate through denitrification. Usually, nitrate becomes reduced and is lost into the atmosphere by denitirification when the redox potential is below 225 mV (Mitsch and Gosselink, 1993). The FGD liner treatment caused significant differences in redox potential ($p < 0.05$) of leachate, showing much lower values in the mesocosms lined with FGD. FGD liner material consists of mostly $CaSO_3$, which is known to be very strong antioxidant that consumes available oxygen (Hao, 1998). This may have resulted in lower redox in lined mesocosms. No difference was observed among the treatments in surface outflow.

Turbidity

Outflow samples were investigated for turbidity (Fig. 7). Turbidity decreased significantly from inflow to outflow in all 20 mesocosms ($p < 0.01$) during the experiment, showing the same tendency observed from the two experimental basins of ORW (Mitsch et al., 1998).

Orthophosphate

More than 80 % of phosphorus input was removed from mesocosms fed by river water inflow, the same pattern as

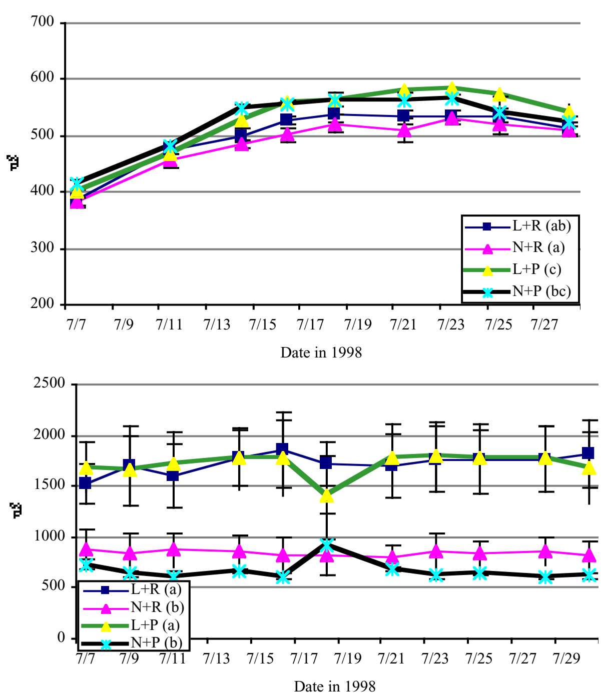

Figure 4. Conductivity of a) outflow and b) leachate in liner vs. no-liner mesocosms during the experiment. Bars indicate standard errors. The same letters among the treatments indicates no statistical difference(L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

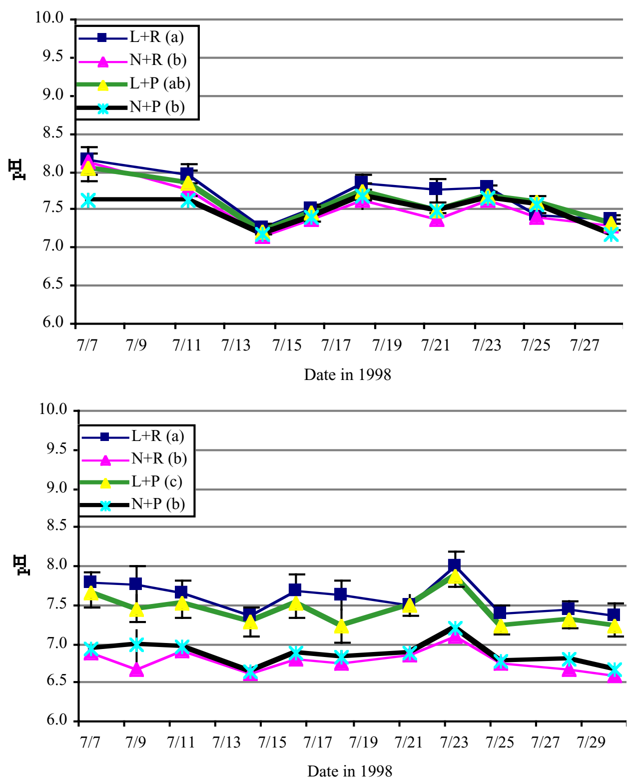

Figure 5. pH of a) outflow and b) leachate in liner vs. no-liner mesocosms during the experiment. Bars indicate standard errors. The same letters among the treatments indicates no statistical difference(L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

Table 2. Water quality and nutrient measurement and changes in the FGD mesocosm experiment, 1997-1998 [a].

Year and parameter	Inflow	Surface outlfow		Percentage change, inflow to outflow		t-test[b]	leachate		Percentage change inflow to leachate		t-test[b]
		liner	no-liner	liner	no-liner		liner	no-liner	liner	no-liner	
First year (1997)											
riverwater											
Temperature, °C	23.92	22.67	22.40	-4.7	-5.8	NS	23.93	23.51	+0.8	-1.0	NS
Turbidity, NTU[c]	27.8	9.4	7.7	-64.2	-69.5	NS					
Dissolved Oxygen, mg/L	6.19	7.11	6.20	+26.8	+10.3	NS	0.44	0.33	-92.8	-94.4	NS
pH	8.72	9.34	9.08	+7.2	+4.2	NS	9.79	7.85	+13.9	+8.6	*
Conductivity, uS/cm	503	548	557	+10.24	+12.32	NS	934	902	+86.8	+83.3	NS
Redox potential, mV	448	409	415	-8.5	-7.0	NS	169	211	-60.1	-51.3	NS
Orthophosphate, mg/L	0.062	0.010	0.008	-83.4	-86.3	NS	0.008	0.012	-87.9	-81.0	*
Total Phosphorus, mg/L	0.140	0.062	0.065	-55	-53.7	NS	0.226	0.201	+71.2	+57.6	NS
Nitrate, mg/L	1.39	0.58	0.52	-56.7	-60.8	NS	0.75	0.58	-41.0	-57.2	NS
Second year (1998)											
riverwater											
Temperature, °C	25.01	24.09	23.83	-3.5	-4.5	NS	23.75	23.19	-4.6	-7.0	NS
Turbidity, NTU	11.66	5.88	5.39	-41.1	-44.9	NS					
Dissolved Oxygen, mg/L	4.90	2.40	2.14	-50.1	-56.4	NS	0.57	0.54	-88.3	-88.8	
pH	7.41	7.67	7.52	+3.6	+1.5	*	7.60	6.81	+2.7	-8.0	*
Conductivity, uS/cm	513.11	505.16	490.90	-2.1	-5	NS	1719.7	847.8	+244.6	+71.9	*
Redox potential, mV	340.89	199.50	201.13	-40.4	-39.9	NS	-10.3	61.3	-104.4	-82.2	*
Orthophosphate, mg/L	0.057	0.011	0.011	-80.9	-81.3	NS	0.002	0.001	-94.9	-97.1	*
Total Phosphorus, mg/L	0.126	0.116	0.157	-5.7	+30.1	NS	0.840	0.717	+584.6	+518.2	NS
Nitrate plus nitrite, mg/L	1.96	0.89	0.74	-47.9	-59.8	NS	0.25	0.23	-83.1	-85.2	NS
P-spiked water											
Temperature, °C	25.56	24.23	24.13	-5.1	-5.5	NS	23.76	23.55	-6.8	-7.6	NS
Turbidity, NTU	17.44	5.36	6.44	-61.3	-54.3	NS					
Dissolved Oxygen, mg/L	4.79	2.99	2.30	-37.1	-51.0		0.60	0.30	-86.8	-93.4	
pH	7.25	7.59	7.48	+4.7	+3.3	NS	7.46	6.88	+2.8	-5.1	*
Conductivity, uS/cm	519.78	533.17	529.13	+1.8	+1.6	NS	1719.9	676.7	+242.1	+34	*
Redox potential, mV	345.56	227.80	230.85	-32.6	-31.1	NS	19.4	42.7	-95.0	-87.8	NS
Orthophosphate, mg/L	2.169	1.082	1.506	-49.1	-29	*	0.000	0.000	-99.9	-100	NS
Total Phosphorus, mg/L	2.850	1.472	2.032	-48.6	-28.6	*	0.313	0.324	-89.6	-88.7	NS
Nitrate plus nitrite, mg/L	2.11	0.66	0.88	-63.2	-54.6	NS	0.27	0.33	-84.2	-79.6	NS

[a] Numbers shown in the table are presented as average of all data collected during the experiment period.
[b]liner versus no-liner; NS, no significant difference at a = 0.05; * significant difference at a = 0.05
[c]NTU, Nephelometric Turbidity Units.

observed in the previous year's study (Table 2). There was no difference between the liner treatment and the control in the phosphorus concentration of surface outflow (Fig. 8a). The outflow from the mesocosms that had P-spiked inflow during the experiment also showed a decrease in the concentration. The liner treatment showed much better performance in phosphorus retention compared to no-liner treatment ($p < 0.05$). More effective Ca-P precipitation may have resulted from the addition of liner material since FGD liner contains more calcium in its composition than do natural clay soils (Ahn et al. 1998).

All leachate showed significant reduction in phosphate concentrations ($p < 0.01$) compared to inflow concentrations (Fig. 8a). Especially under the high-P loading, phosphate removal efficiency was 100 % whether or not the mesocosms were lined with FGD. Most of the orthophosphate concentrations of leachate remained under the detection limit, resulting in more than a 90 % removal rate regardless of the treatments in the second year.

Total phosphorus

Total phosphorus was more effectively removed from P-spiked surface water passing through wetland mesocosms lined with FGD by-product than through those with no FGD liner (Fig. 9). The same tendency was observed in the mesocosms with river water inflow, but the difference in phosphorus removal between lined and unlined mesocosms was not significant.

Compared to the pattern of the first year, the removal efficiency of total phosphorus from the mesocosms fed by river water dropped greatly and the system seemed to start becoming a source of phosphorus rather than a sink in the second year. Interestingly, this tendency was also vivid in the leachate. The leachate samples from the mesocosm fed by river water showed tremendous increase in their concentration of total phosphorus compared to inflow (Table 2). It seems that the system was adding more phosphorus to the water while the water was passing through the soil plus FGD liner complex.

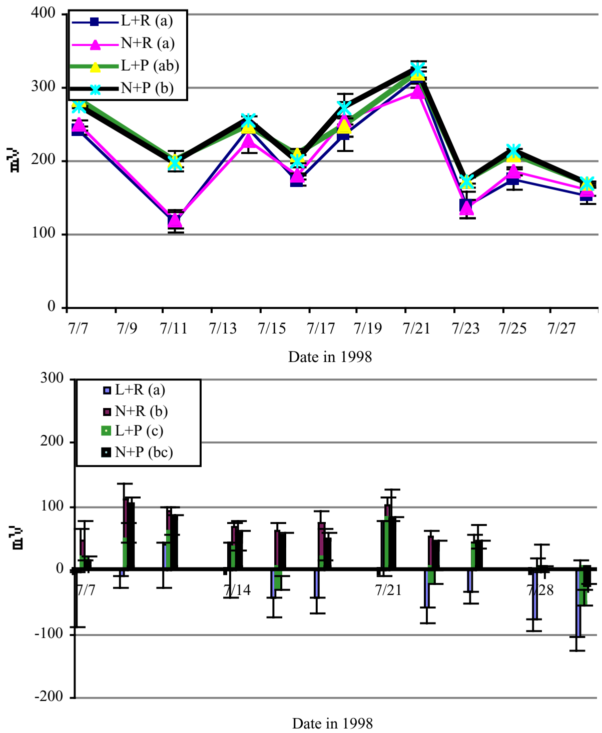

Figure 6. Redox a) outflow and b) leachate in liner vs. no-liner mesocosms during the experiment. Bars indicate standard errors. The same letters among the treatments indicates no statistical difference(L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

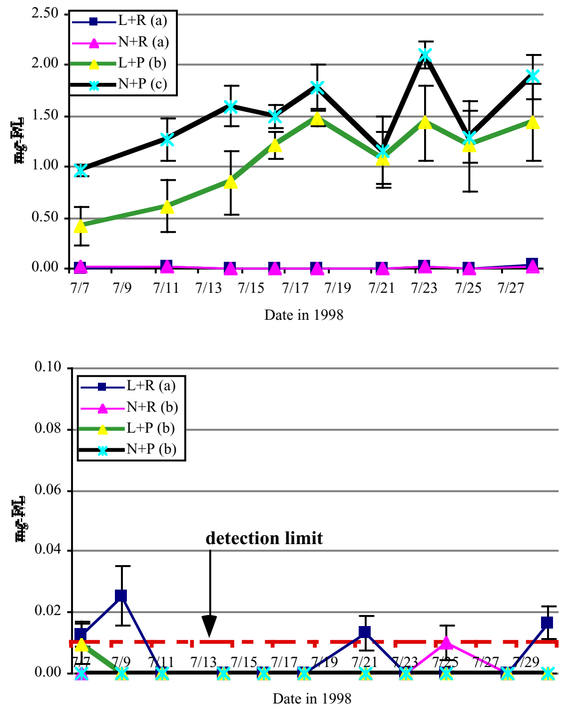

Figure 8. orthophosphate of a) outflow and b) leachate in liner vs. no-liner mesocosms during the experiment. Bars indicate standard errors. The same letters among the treatments indicates no statistical difference(L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

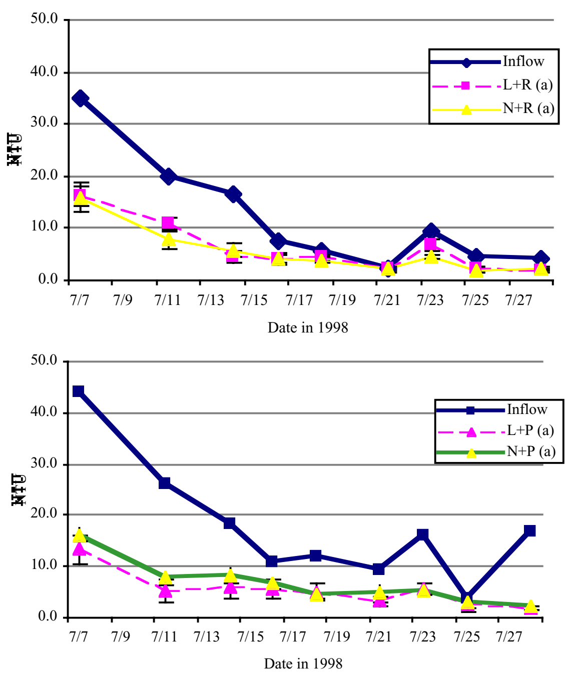

Figure 7. Turbidity of a) outflow and b) leachate in liner vs. no-liner mesocosms during the experiment. Bars indicate standard errors. The same letters among the treatments indicates no statistical difference(L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

Nitrite plus nitrate (NO_2 +NO_3-N)

The reduction of nitrate from inflow to both outflow and leachate was significant ($p < 0.01$) (Table 2). Lower redox in the leachate (Fig. 6b) indicates that redox was low enough for nitrates to be reduced by denitrification because anaerobic sediments are the perfect habitat for various denitrifying bacteria. Uptake of nitrate by the plants also partially contributes to the removal of nitrogen out of water. No significant difference in nitrogen removal was observed in both outflow and leachate among the treatments (Fig. 10).

Plant morphometry

Wetland vegetation (*Schoenoplectus tabernaemontani*) still showed lower average stem length and fewer stems bearing flowers in mesocosms using FGD by-product as liners in the second year (Table 3), the same results as those from the first year (Ahn et al., 1998). However, number of stems growth was not significantly different between the FGD lined mesocosms and the unlined mesocosms (Table 2) showing that the plants may have overcome the possible phytotoxicity or growth retardation caused by FGD in the first year.

Plant biomass

There was no difference in biomass (belowground, aboveground, and total) of wetland plant between lined and unlined mesocosms in either river water or phosphorus-

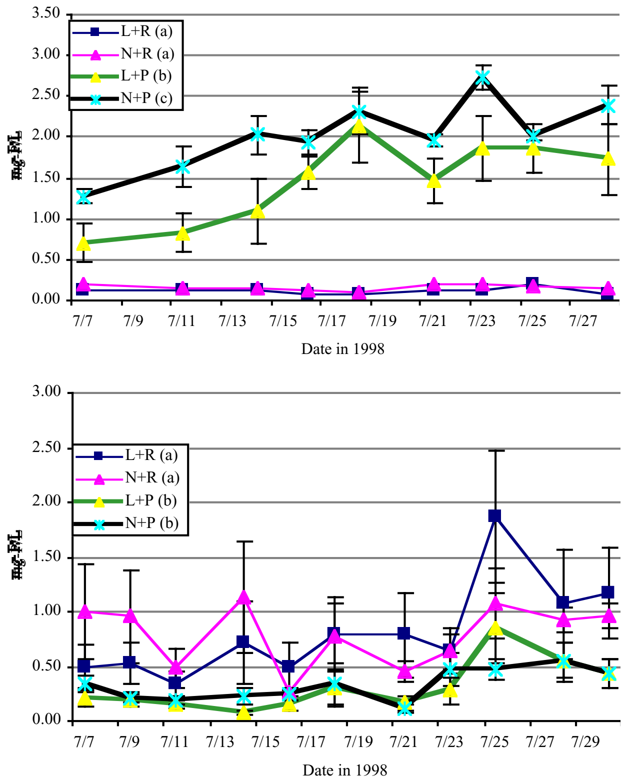

Figure 9. Total phosphorus of a) outflow and b) leachate in liner vs. no-liner mesocosms during the experiment. Bars indicate standard errors. The same letters among the treatments indicates no statistical difference (L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

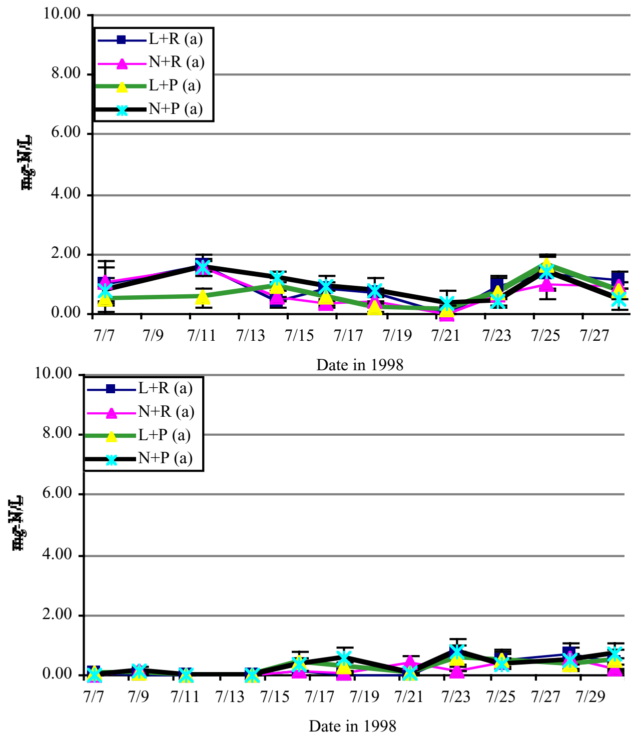

Figure 10. Nitrite plus nitrate of a) outflow and b) leachate in liner vs. no-liner mesocosms during the experiment. Bars indicates standard errors. The same letters among the treatments indicates no statistical difference (L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

spiked inflows at the end of two years' experiments (Fig. 11). Aboveground biomass showed a slightly lower values in lined mesocosms compared to unlined mesocosms, but the difference was not significant ($p = 0.094$).

Plant tissue analysis

The ICP analysis for plant tissue material is summarized in Table 4 according to the treatments. In the analysis of aboveground tissue, significantly higher concentration of Fe, Li, and lower concentration of Mo, Na were observed in the mesocosms lined with FGD ($p < 0.05$). There were several elements that showed significant difference in the tissue concentration of belowground biomass between liner treatments (Table 4). Al, B, Ba, Ca, Co, Cr, Fe, Li, Mg, S, Si, Sr, V, and Zn increased significantly in plants grown in mesocosms lined with FGD ($p < 0.05$). Aboveground and belowground biomass indicated that these major and trace elements supplied by the addition of FGD liner did not exert any significantly negative impact on biomass production of (Fig. 11).

Boron, which has caused concern as an element causing phytotoxicity at high dosage, was not different in the aboveground tissue of the plants in either lined and unlined wetlands. However, boron of belowground tissue was significantly higher in the lined mesocosms compared to unlined mesocosms ($p < 0.05$). Boron is known to be highly

Table 3. Number of stems, number of stems bearing flowers and stem length of *S. tabernaemontani* under various treatment regime. Standard error is shown following mean in ( ). Means in each row followed by the same letter are not significantly different across the treatments at the $p < 0.05$ level.

Variable	Treatment			
	L + R	N + R	L + P	N + P
No. of stems	282 (20) [a]	304 (22) [a]	255 (17) [b]	289 (9) [a]
No. of stems(with flowers)	266 (17) [b]	299 (19) [a]	232 (15) [c]	284 (8) [ab]
Stem length(cm)	102.2 (2.2) [c]	112.5 (2.1) [a]	107.6 (3.6) [b]	113.4 (3.4) [a]

L+R = liner + riverwater; N+R = no-liner + riverwater; L+P = liner + p-spiked; N+P = no-liner + P-spiked

Table 4. ICP analysis of plant tissue material(average± std error)(L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

	Unit	L+R	N+R	L+P	N+P
Above groundtissue analysis					
N	%	0.93±0.03	0.98±0.02	1.04±0.02	0.96±0.07
Al	ppm	53±17	51±16	106±31	69±13
As	ppm	2.69±0.37	2.37±0.16	1.51±0.33	2.19±0.40
B	ppm	11.9±1.0	14.3±1.8	14.7±2.0	11.4±0.3
Ba	ppm	42.4±7.3	35.3±2.9	31.9±3.4	38.1±1.8
Ca	ppm	5141±493	5391±365	5703±613	4877±166
Co	ppm	0.331±0.070	0.161±0.158	0.210±0.116	0.069±0.083
Cd	ppm	ND*	ND	ND	ND
Cr	ppm	1.20±0.35	0.48±0.04	0.90±0.08	0.59±0.02
Cu	ppm	23.88±9.91	4.78±0.87	8.09±4.17	12.60±9.28
Fe	ppm	382±95	167±37	331±79	233±40
K	ppm	14777±495	13689±996	14725±1003	15424±563
Li	ppm	0.835±0.034	ND	1.167±0.204	0.813**
Mg	ppm	804±61	852±71	930±110	870±43
Mn	ppm	1543±184	1210±101	1395±169	1382±231
Mo	ppm	2.77±0.38	10.80±3.66	3.72±2.21	10.45±2.82
Na	ppm	407±69	597±88	385±63	494±45
Ni	ppm	45.2±22.6	3.7±1.1	20.3±16.0	23.3±21.6
P	ppm	1285±31	1229±59	1752±125	1661±146
Pb	ppm	13.68±3.80	7.08±0.01	13.35±11.79	8.69±4.41
S	ppm	2521±179	2216±249	2604±243	2229±239
Si	ppm	31.30±0.98	33.92±1.39	34.67±1.51	30.98±2.23
Sr	ppm	40.77±5.28	41.04±4.05	44.01±6.41	46.85±1.74
V	ppm	0.592±0.151	0.472±0.061	0.543±0.056	ND
Zn	ppm	34.69±9.95	20.30±2.24	13.01±0.42	12.98±1.25
Belowground tissue analysis					
N	%	0.53±0.04	0.52±0.04	0.55±0.02	0.54±0.04
Al	ppm	2832±745	1399±332	2560±718	1355±256
As	ppm	27.23±2.76	20.59±5.03	28.61±8.70	27.19±4.76
B	ppm	11.1±1.5	8.2±0.6	9.2±2.7	7.7±0.5
Ba	ppm	42.6±7.1	26.8±4.1	39.1±12.5	31.0±3.6
Ca	ppm	3317±447	2436±256	3135±994	2543±225
Co	ppm	1.227±0.139	1.253±0.217	1.244±0.336	1.260±0.072
Cd	ppm	3.654±0.535	2.958±0.383	3.789±1.113	3.010±0.364
Cr	ppm	4.43±0.99	3.20±0.91	4.16±1.08	2.48±0.43
Cu	ppm	8.25±0.91	7.49±0.66	7.83±2.04	8.10±0.35
Fe	ppm	14952±1527	9941±1955	13867±4291	12017±1994
K	ppm	11208±574	10543±852	7864±2030	10124±1110
Li	ppm	2.778±0.379	1.333±0.218	2.044±0.594	1.513±0.205
Mg	ppm	1486±148	1287±87	1156±320	1121±57
Mn	ppm	596±51	576±39	565±165	598±28
Mo	ppm	4.58±0.50	4.43±0.53	4.48±1.28	6.61±1.55
Na	ppm	916±28	1161±116	839±226	957±132
Ni	ppm	9.7±1.9	6.9±1.5	10.4±3.7	7.5±2.4
P	ppm	1724±198	1818±146	1391±365	1985±71
Pb	ppm	7.17±1.26	8.64±4.95	7.10±0.95	14.57±9.85
S	ppm	2088±248	1704±131	1806±567	1495±101
Si	ppm	47.03±7.91	33.75±2.79	38.10±10.49	30.51±3.09
Sr	ppm	44.85±4.13	35.51±2.98	41.39±12.45	39.99±3.35
V	ppm	7.603±1.808	4.276±0.784	7.466±2.189	4.547±0.705
Zn	ppm	45.39±10.63	26.21±2.11	29.44±9.51	25.10±1.26

The sample size was five for all treatments except L+P, ofwhich sample size was four. *ND indicates the concentration of the elementw as below the detection limit. ** indicates the number of samples detected for the element was one.

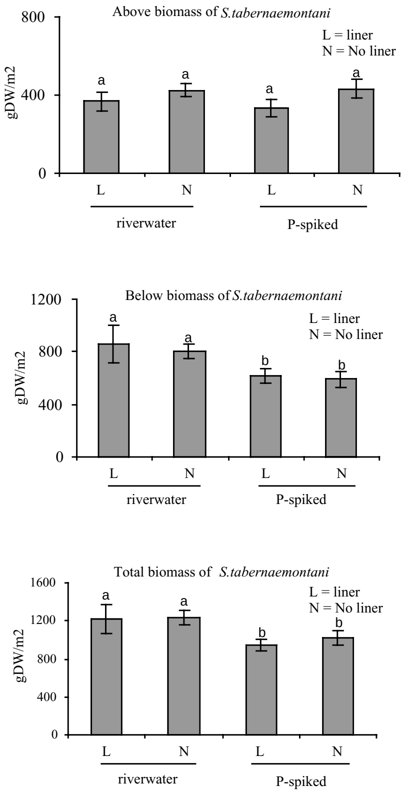

Figure 11. Biomass production from two year study of FGD mesocosm experiment. Bars indicate standard errors. The same letters among the treatments indicates no statistical difference.

phytotoxic in some plants (Nable et al., 1997) and can cause serious problems to plants grown on soils irrigated with high-boron water (Gupta et al., 1985) and some saline soils, and plants growing on Pulverized Fuel Ash (PFA or fly ash) (El-Mogazi et al., 1988). Boron toxicity has been well-studied in agricultural crops and fruit trees, but research on wetland plants is rare (Sposito, 1988). McLeod and Ciravolo (1998) tested bottomland tree seedlings for boron tolerance and potential boron removal. The higher tissue content of boron in the belowground biomass from liner mesocosms did not seem to affect negatively on biomass production.

Surface soil analysis

The elemental analysis of surface soil is summarized in Table 5. Al, Ca, and Ni showed significant treatment effects of the liner ($p < 0.05$). Soil Ca was higher in the lined mesocosms, whereas Al and Ni were lower in the lined mesocosms. Higher Ca content of the surface soil in the lined treatment seemed to contribute to the immobilization of phophorus, lowering the phosphorus concentration of outflow water through increased Ca-P precipitation (Fig. 9a). Low Al concentration in the soil seems attributed to plant uptake since there was significantly higher content of Al in the tissues of plants grown ($p = 0.005$) in the lined mesocosms. Wendell and Ritchey (1996) found that high-calcium FGD products reduced aluminum toxicity in soil due to increased pH (Hsu, 1977) and precipitation of soil Al-sulfates. This could be a contributing factor to the lower

Table 5. ICP analysis of surface soil element (average± std error)(L = FGD liner; N= no liner; P = phosphorus-spiked river water; R = river water).

	Unit	L+R	N+R	L+P	N+P
Al	ug/g	484 ±17	525 ±12	480 ±28	524 ±16
As	ug/g	0.21**	ND*	0.400 ±0.101	0.216 ±0.065
B	ug/g	1.502 ±0.167	1.378 ±0.064	1.246 ±0.113	1.259 ±0.085
Ba	ug/g	17.23 ±3.11	21.89 ±3.90	16.96 ±3.76	17.77 ±4.46
Ca	ug/g	2858 ±203	2169 ±45	3251 ±545	2745 ±263
Cd	ug/g	0.259 ±0.042	0.259 ±0.033	0.227 ±0.049	0.277 ±0.038
Co	ug/g	1.435 ±0.068	1.539 ±0.091	1.451 ±0.134	1.560 ±0.111
Cr	ug/g	0.212 ±0.020	0.210 ±0.053	0.228 ±0.012	0.245 ±0.036
Cu	ug/g	5.44 ±0.72	5.14 ±0.83	5.10 ±0.90	5.18 ±0.80
Fe	ug/g	416 ±18	414 ±31	422 ±30	421 ±23
K	ug/g	76.5 ±7.7	93.1 ±11.1	78.4 ±5.2	87.3 ±11.2
Mg	ug/g	362 ±8	369 ±10	342 ±6	351 ±7
Mn	ug/g	128 ±13	110 ±8	126 ±15	102 ±14
Mo	ug/g	0.061**	0.165 ±0.068	0.062**	0.154 ±0.035
Na	ug/g	74.0 ±3.1	73.1 ±4.2	71.8 ±4.0	73.8 ±1.2
Ni	ug/g	3.119 ±0.071	3.411 ±0.105	3.407 ±0.134	3.563 ±0.091
P	ug/g	7.130 ±0.344	8.524 ±0.519	9.218 ±1.032	11.476 ±1.335
Pb	ug/g	3.846 ±1.330	3.760 ±1.115	3.023 ±1.258	3.400 ±1.194
S	ug/g	322 ±51	221 ±41	396 ±132	372 ±88
Si	ug/g	182 ±7	189 ±4	189 ±8	192 ±4
Sr	ug/g	23.1 ±1.7	21.2 ±1.2	26.3 ±3.7	26.0 ±2.3
V	ug/g	0.989 ±0.059	0.923 ±0.048	1.159 ±0.015	1.198 ±0.068
Zn	ug/g	7.737 ±0.875	7.270 ±0.328	6.979 ±0.394	7.404 ±0.455

concentration of Al in the surface soil if the precipitation occurred in the bottom layer of the soil near the FGD liner. Soil amendment with $CaSO_4$ or $CaSO_3$ FGD products reduced Al toxicity and overcame Ca deficiency in their investigation. Ni was also higher in the tissue of plants grown in the lined mesocosms, but the difference was not significant (p = 0.093). Some other mechanisms such as leaching may have contributed to the decreased concentration of this element in soil. In the mesocosms with high-P inflow, phosphorus concentrations of the surface soil were significantly higher as expected. Vanadium (V) was also in the high-P mesocosms.

Conclusions

The FGD mesocosm experiment for the second year showed the possibility that this FGD by-product can be reused in constructed wetlands as a liner.

These small mesocosm studies suggested some positive results that could be achieved in constructed wetlands using FGD products, especially the increased uptake of phosphorus in both leachate (first year) and surface water (second year). Also, there was no difference in biomass of wetland plant between lined and unlined mesocosms, although lower average stem length and fewer stems bearing flowers were observed in mesocosms with FGD as liners. A larger-scale, long-term wetland experiment close to full scale is suggested from the two-year mesocosm study to better predict what would happen if FGD liner material were used on full scale wetland basins in a real situation.

Acknowledgments

The authors wish to thank Mike Brady, Chris Moody, Gregg Sablak, Katie Kleber, and Eric Domyan for their help through the second-year experiment. The work described in this paper is a part of the research project entitled "Re-Use of Clean Coal Technology By-Products in the Construction of Impervious Liners" (OCDO Grant CDO/D-95-10), William E. Wolfe and William J. Mitsch, co-principal investigators, and was performed at the Olentangy River Wetland Research Park at The Ohio State University. The principal sponsor of the research project is the Ohio Coal Development Office within the Ohio Department of Development.

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